

MGGPOD: A MONTE CARLO SUITE FOR GAMMA-RAY ASTRONOMY

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ABSTRACT

We have developed MGGPOD, a user-friendly suite of Monte Carlo codes built around the widely used GEANT (Version 3.21) package. The MGGPOD Monte Carlo suite and documentation are publicly available for download. MGGPOD is an ideal tool for supporting the various stages of gamma-ray astronomy missions, ranging from the design, development, and performance prediction through calibration and response generation to data reduction. In particular, MGGPOD is capable of simulating *ab initio* the physical processes relevant for the production of instrumental backgrounds. These include the build-up and delayed decay of radioactive isotopes as well as the prompt de-excitation of excited nuclei, both of which give rise to a plethora of instrumental gamma-ray background lines in addition to continuum backgrounds.

Key words: gamma-ray astronomy; Monte Carlo simulation; instrumentation.

1. INTRODUCTION

Intense and complex instrumental backgrounds, against which the much smaller signals from celestial sources have to be discerned, are a notorious problem for low and intermediate energy gamma-ray astronomy (~ 50 keV – 10 MeV). Therefore a detailed qualitative and quantitative understanding of instrumental line and continuum backgrounds is crucial for most stages of gamma-ray astronomy missions, ranging from the design and development of new instrumentation through performance prediction to data reduction. A promising approach for obtaining quantitative estimates of instrumental backgrounds is *ab initio* Monte Carlo simulation (see e.g. Dean et al., 2003).

We have developed a suite of Monte Carlo packages, named MGGPOD (Weidenspointner et al., 2003, 2004), that supports this type of simulation. The MGGPOD Monte Carlo suite (version 1.0) and documentation are publicly available for download from <http://sigma-2.cesr.fr/spi/MGGPOD/>. In this paper we provide an overview of the capabilities, functioning, and structure of the MGGPOD package, and give examples of applications to past and present gamma-ray missions.

2. THE MGGPOD MONTE CARLO SIMULATION SUITE

The MGGPOD Monte Carlo suite allows *ab initio* simulations of instrumental backgrounds – including the many gamma-ray lines – arising from interactions of the various radiation fields within the instrument and spacecraft materials. It is possible to simulate both prompt instrumental backgrounds, such as energy losses of cosmic-ray particles and their secondaries, as well as delayed instrumental backgrounds, which are due to the decay of radioactive isotopes produced in nuclear interactions. Of course, MGGPOD can also be used to study the response of gamma-ray instruments to astrophysical and calibration sources. The MGGPOD suite is therefore an ideal Monte Carlo tool for gamma-ray astronomy. A detailed description of the physics of the MGGPOD Monte Carlo suite can be found in Weidenspointner et al. (2004). The documentation available from the MGGPOD web site provides comprehensive practical advice for users. First applications of MGGPOD have been presented in Weidenspointner et al. (2003, 2004).

2.1. Capabilities and Functionalities

MGGPOD is a suite of five closely integrated Monte Carlo packages, namely **MGEANT**, **GALOR**,

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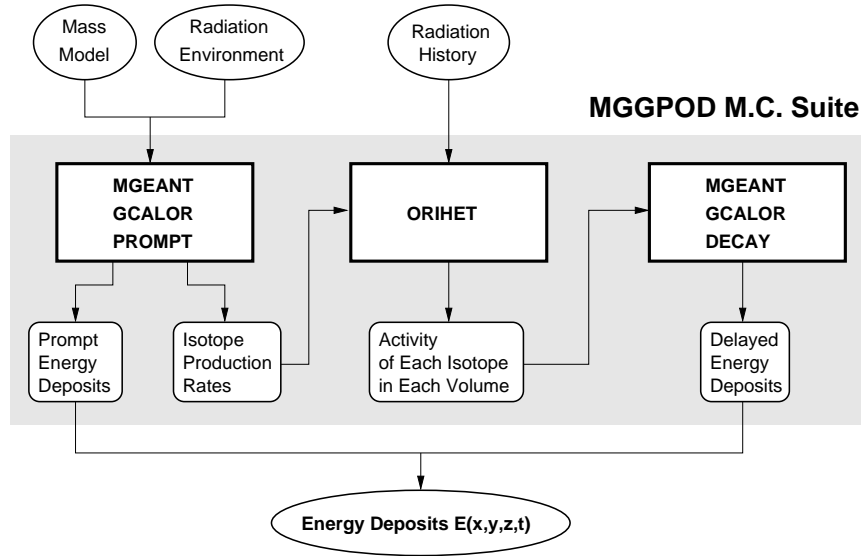


Figure 1. A flow chart illustrating the overall structure of the MGGPOD Monte Carlo simulation suite. The various simulation packages (shown in boxes) and input and output files (shown in ellipses and round-edged boxes) are explained in the text

PROMPT, ORIET, and DECAY. The MGGPOD suite resulted from a combination of the NASA/GSFC MGEANT (Sturmer et al., 2000) and the University of Southampton GGOD (Dean et al., 2003) Monte Carlo codes, which we supplemented with the newly developed PROMPT package. All these packages are based on the widely used GEANT Detector Description and Simulation Tool (Version 3.21) created and supported at CERN¹, which is designed to simulate the passage of elementary particles through an experimental setup.

In a nutshell, the capabilities and functions of the five packages that constitute the MGGPOD suite are as follows:

- MGEANT is a multi-purpose simulation package that was created to increase the versatility of the GEANT simulation tool. A modular, “object oriented” approach was pursued, allowing for rapid prototyping of detector systems and easy generation of most of the radiation fields relevant to gamma-ray astronomy. Within the MGGPOD suite, MGEANT (i.e. GEANT) stores and transports all particles, and treats electromagnetic interactions from about 10 keV to a few TeV. MGEANT provides the option of using the GLECS package² to take into account the energy of bound electrons in Compton scatterings. The MGEANT simulation package and a user manual are available at a NASA/GSFC web site³.
- GCALOR (Zeitnitz and Gabriel, 1994) simulates hadronic interactions down to 1 MeV for

nucleons and charged pions and down to thermal energies (10^{-5} eV) for neutrons. Equally important, this package⁴ provides access to the energy deposits from all interactions as well as to isotope production anywhere in the simulated setup.

- PROMPT simulates prompt photon emission associated with the de-excitation of excited nuclei produced by neutron capture, inelastic neutron scattering, and spallation.
- ORIET, originally developed for the GGOD suite and improved for MGGPOD, calculates the build-up and decay of activity in any system for which the nuclide production rates are known. Hence ORIET can be used to convert nuclide production rates, determined from simulations of cosmic-ray irradiation, to decay rates. These are required input for simulating the radioactive decays giving rise to delayed background.
- DECAY, again originally developed for GGOD and improved for our purposes, enables MGGPOD to simulate radioactive decays.

2.2. Structure

The overall structure of the MGGPOD package is illustrated in Fig. 1. Depending on the simulated radiation field or gamma-ray source distribution one or three steps, requiring two or three input files, are needed to obtain the resulting energy deposits in the detector system under study. In general, it is advisable to simulate each component of the radiation environment separately. MGGPOD distinguishes two

¹see <http://wwwinfo.cern.ch/asd/geant/>

²see <http://nis-www.lanl.gov/~mkippen/actsim/glecs/> by R.M. Kippen

³see <http://lhea-www.gsfc.nasa.gov/docs/gamcosray/legr/mgeant/mgeant.html>

⁴see <http://www.physik.uni-mainz.de/zeitnitz/gcalor/gcalor.html>

classes of radiation fields. Class I comprises radiation fields for which only prompt energy deposits are of interest, such as celestial or laboratory gamma-ray sources or cosmic-ray electrons. Class II comprises radiation fields for which in addition delayed energy deposits resulting from the activation of radioactive isotopes need to be considered. Examples for Class II fields are cosmic-ray protons, or geomagnetically trapped protons.

For both of these classes, the simulation of the prompt energy deposits requires two input files: a mass model, and a model of the simulated radiation field. The mass model is a detailed computer description of the experimental setup under study. It specifies the geometrical structure of instrument and spacecraft, the atomic and/or isotopic composition of materials, and sets parameters that influence the transport of particles in different materials. Each component of the radiation environment (and analogously for gamma-ray sources) to which the instrument is exposed is characterized by three quantities: the type of the incident particles, and their spectral and angular distributions. The prompt energy deposits are written to an output event file; in case of a Class II radiation field there is an additional output file in which all the nuclei produced in hadronic interactions are recorded.

To simulate delayed energy deposits (Class II radiation field) two additional steps need to be taken. These require as input the time history of the radiation field which is responsible for the activation, and the previously calculated isotope production rates. Based on this information first the activity of each isotope produced in each structural element of the mass model is determined. Then these activities are used to simulate the delayed energy deposits due to radioactive decays in the instrument.

Combining prompt and delayed energy deposits from each component of the radiation environment and gamma-ray sources, it is possible to obtain the total energy deposited in the system as a function of position and time.

3. PRACTICAL CONSIDERATIONS

This section addresses some of the practical considerations a potential user of MGGPOD might have. It is a synopsis of the documentation available from the MGGPOD web site.

Installation of the complete MGGPOD package (software and data files) requires little more than 100 MB of disk space. The documentation provides detailed installation instructions, including the installation of the required CERNLIB and other libraries which are necessary to build, but are not included in, the MGGPOD package. The MGGPOD software is written in the FORTRAN 77 and C programming languages; in addition there are a few C shell scripts. The source code is completely open

and transparent, allowing the user to adapt, change, and improve the code. In fact, a few customizations and adjustments of the code are inevitable when simulating different instruments. These unavoidable changes are described in the documentation. The format of both the event and activation output files is FITS. MGGPOD inherited the interactive display capabilities of (M)GEANT, which are based on CERN's PAW++ package. This is a very convenient feature when creating a mass model, or when specifying the parameters of a radiation field ("beam").

To facilitate the use of MGGPOD by novice users the release contains examples for all simulation steps outlined in Sec. 2.2. The examples include all input and output files, and instructions on how to build and run the necessary executables.

As described in Sec. 2.1, different modules of MGGPOD simulate different physical processes which can be treated over different energy ranges. The MGGPOD input file allows the user to define low-energy cutoff values for the tracking of five different particle types: photons, electrons, neutral and charged hadrons, and muons. We recommend to use as default low-energy cutoff values 10 keV for photons, electrons, and muons, 10^{-2} eV for neutral hadrons, and 1 MeV for charged hadrons. Experienced users can lower these thresholds, in particular for photons.

For many applications of MGGPOD the computation time needed to complete a simulation is an important consideration. The speed of MGGPOD Monte Carlo simulations varies greatly with the type and energy of the incident particle (which affect e.g. the number of secondary particles that are produced and tracked), with the physical volume and mass described in the mass model (but less with geometrical complexity), and of course with the speed of the computer employed. As an example, for the TGRS and SPI mass models, using a 1.6 GHz CPU, typically about 3×10^{-3} CPU seconds and 2×10^{-2} CPU seconds are needed to simulate the interactions of a cosmic-ray proton, respectively. The difference in processing time is mainly due to the fact that INTEGRAL/SPI is a much heavier and complex instrument than WIND/TGRS. For both models the time needed to simulate an incident gamma-ray photon, or a radioactive decay, is about ten times shorter than the respective proton processing time. The computation time for a simulation also depends on the desired statistics in the result; better statistics require the simulation of more particles and consequently more processing time. For SPI, about 10^7 photons, requiring a computation time of about 8 CPU hours, in a homogeneous beam covering the 19 Ge detectors are sufficient for simulating the instrument response at a given energy. When simulating the activation of INTEGRAL and SPI by cosmic-ray protons, 10^7 protons, requiring a computation time of about 3 CPU days (and representing about 21 s of actual in-orbit irradiation), provide acceptable statistics for calculating nuclide production rates, and enough statistics in the detector count rate to ob-

tain a crude spectrum. Detailed studies of prompt background line production by cosmic-ray protons require multiple simulation runs.

The MGGPOD web site also provides off-the-shelf model spectra for two common radiation fields: cosmic-ray protons (at solar minimum and maximum, based on Moskalenko et al., 2002), and the diffuse cosmic X-ray and gamma-ray emission (based on Gruber et al., 1999). For missions in low-Earth orbit albedo radiations (most importantly neutrons and gamma rays) and geomagnetically trapped particles need to be considered in addition. The web site provides links to the ESA Space Information System (SPENVIS) and the NASA Space Ionizing Radiation Environments and Shielding Tools (SIREST), which can be used to obtain radiation field models for missions in a low-Earth environment. Users should be aware that the space environment is not stable. Detailed simulations require that input particle spectra reflect conditions in a given orbit and at a given phase of the solar cycle (including the polarity of the heliosphere for cosmic-ray protons, Moskalenko et al., 2002). Currently, GCALOR does not treat hadronic interactions for alpha particles or heavier cosmic rays. If diffuse cosmic X-rays are an important background component, the uncertainty in the simulation result is usually dominated by uncertainties in the photoelectric absorption in materials surrounding the detectors as defined in the mass model.

4. APPLICATIONS OF MGGPOD

The MGGPOD Monte Carlo suite has been, and is being, applied to model the instrumental backgrounds of several gamma-ray missions. Using the MGGPOD codes, very good agreement between the Monte Carlo results and the actual data of the Transient Gamma-Ray Spectrometer (TGRS) on board *Wind* (Owens et al., 1995) has been obtained, as discussed in Weidenspointner et al. (2003, 2004). As an example, in Fig. 2 we show a comparison of MGGPOD simulations with TGRS data. First modelling results for the SPI Spectrometer on board the ESA INTEGRAL observatory (Vedrenne et al., 2003) again yielded good agreement, but also indicate remaining deficiencies with respect to the production and thermalization of secondary neutrons in a massive spacecraft and/or instrument (Weidenspointner et al., 2003). Both of these instruments operate in highly elliptical orbits above the Earth's radiation belts.

Recently, the MGGPOD suite has been applied to modelling the instrumental background of the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI, described in Smith et al., 2002). This is the first time MGGPOD is used for modelling the instrumental background of an instrument in low-Earth orbit. This case is particularly difficult because activation during passages through the South-Atlantic Anomaly (SAA) gives rise to

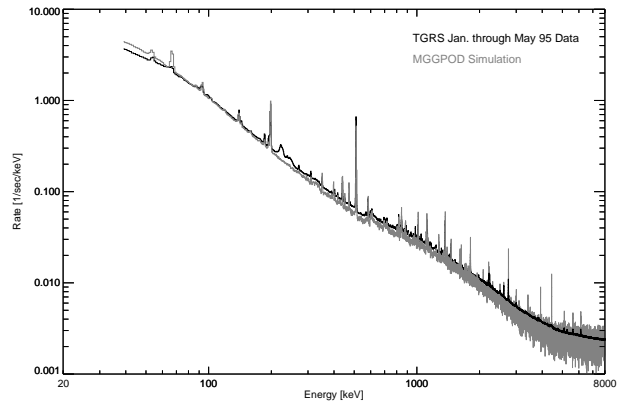


Figure 2. A comparison of the January–May 1995 TGRS spectrum with a MGGPOD simulation, taken from Weidenspointner et al. (2003). The broad features in the data between 210 and 260 keV are electronic artefacts

a strong and time-variable background component. Unlike all other components of the radiation environment, the time-variability of the SAA-induced backgrounds needs to be accounted for in the simulations. Preliminary modelling results are presented by Wunderer et al. (2004) at this workshop.

5. SUMMARY

The MGGPOD Monte Carlo suite is an ideal tool for supporting the various stages of gamma-ray astronomy missions, ranging from the design, development, and performance prediction through calibration and response generation to data reduction. The MGGPOD software and documentation are publicly available for download at CESR. The package has been, and is being, successfully applied to several past and present gamma-ray missions.

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